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Flight Test of Radar Altimeter Enhancement for Terrain-Referenced Guidance

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Aircraft operations at low altitude near the terrain require high pilot workload and are inherently of high risk, even in fair weather and nonhostile environments. To reduce crew workload and allow safer flight in this regime, an automated guidance system was developed that presents a low-altitude trajectory to the pilot on a helmet-mounted display. The guidance trajectory is generated by employing a digital terrain elevation map subject to mission requirements and aircraft performance limits. The flight envelope of this system is principally limited by accuracy in above ground level (AGL) positioning of the aircraft. Errors of the terrain elevation map and airborne navigation systems restricted flight to above 300 ft AGL. In this work, a Kalman filter state estimator has been developed that blends a radar altimeter with the airborne navigation and stored terrain elevation data for improved AGL positioning. This AGL altitude state estimator was integrated in a near-terrain guidance system aboard a U.S. Army helicopter and flight tested in moderately rugged terrain over a variety of flight and system conditions. The minimum operating altitude of this terrain database referenced guidance system was reduced to 150 ft with the addition of this radar altimeter-based Kalman filter state estimator.

Introduction

A VARIETY of civilian and military aircraft regularly conduct missions near the terrain at low altitude. Airborne fire fighting, police surveillance, search and rescue, and helicopter emergency medical service all involve flight in this regime as an essential element of their flight profile. Flights are commonly canceled due to weather or pilot–aircraft limitations that restrict flights to above local terrain maximums. For the military, operations at low altitude near the terrain are necessary to increase covertness while penetrating enemy territory. Increased survivability and payload effectiveness can also be achieved. Both communities suffer from accidents referred to as controlled flight into terrain (CFIT), whereby a fully functioning aircraft is inadvertently flown into the ground due to pilot error, typically during approach to landing.

Avionic aids for these missions employ active and passive sensors, specialized display devices, and digital terrain elevation maps in assorted combinations. Levels of automation range from head-down display of minimally processed sensor data to full-authority autopilot systems. Military programs have generated the widest array and most extensive use of low-altitude avionic systems. Terrain avoidance (TA) radars provide a top-down view of terrain above a given clearance plane. The pilot maneuvers the aircraft clear of these areas by monitoring this radar display, which presents terrain greater than the reference altitude as a bright area. Terrain-following (TF) radars allow automatic contour [constant above ground level (AGL)] flight by sending control commands to the aircraft for safe climb/dive over terrain or obstacles in the flight path. The pilot is also given a display for TF monitoring or for manual operation. Such decoupled lateral (TA) or vertical (TF) maneuvering systems are operational in aircraft such as the A-7, F-111, and B-1.[1,2]

Integrated lateral and vertical flight can be achieved by using a digitized terrain elevation map. By applying a cost function over an intended route between waypoints, a three-dimensional TF/TA route may be calculated. The U.S. Air Force, among others, has developed and demonstrated this capability for aircraft and missile applications.[3,4]

The use of a radar altimeter with digital terrain elevation maps has received much attention. Perhaps the most successful application of terrain elevation databases has been for terrain-referenced navigation, where radar altimeter returns are used to achieve a positional fix within a given terrain database.[5] Recent ground proximity systems predict whether an aircraft's flight path is headed for a collision with the terrain by monitoring radar altimeter returns and aircraft's location within a digital terrain map. Such systems have both civilian[6] and military[7] application.

A low-altitude TF/TA guidance system for helicopters has been under development at NASA Ames Research Center.[8] The guidance algorithm uses mission requirements, aircraft performance capabilities, airborne navigation, and digitized terrain elevation data to generate a low-altitude, valley-seeking trajectory. It seeks to minimize mean sea level (MSL) altitude, heading change from a straight-line nominal path between waypoints, and lateral offset from the nominal path. This trajectory is generated in real time and presented to the pilot on a helmet-mounted display. The system's performance is principally limited in its ability to position itself above the terrain and its inability to detect and avoid unmapped obstacles, such as trees and wires. The above-ground positioning limitation was found dominant and restricted flight to above 300 ft AGL at the operational design speeds between 80 and 110 knots.

Although the guidance trajectory is derived from a terrain elevation map, the AGL positioning of the aircraft is found from the difference between airborne navigation MSL altitude and the predicted terrain map elevation below the aircraft. To improve AGL aircraft positioning, a Kalman filter was developed that blends radar altimeter measurements, navigation system vertical position, and stored digital terrain data. The result is a more accurate estimate of

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AGL altitude for the TF/TA guidance system. The linear, sequential measurement processing Kalman filter was implemented in a test helicopter and extensively flight tested in moderately rugged terrain. The Kalman filter processing of the radar altimeter was found to substantially reduce the AGL positioning limitation of the aforementioned guidance system, leaving the flight envelope constraint imposed by obstacle detection and avoidance. Minimum operational altitude was reduced to 150 ft at the operational speeds between 80 and 110 knots with the addition of this radar altimeter-based state estimator.

The paper begins with the problem formulation and Kalman-filter-augmented guidance system description. State models are then developed and the Kalman filter defined. The aircraft implementation is then described and its in-flight, real-time performance is appraised. Concluding remarks and future directions are then discussed.

Problem Description

Figure 1 describes key variables and definitions involved in the low-altitude, terrain-referenced flight environment. The aircraft is depicted on a nominal flight path with AGL altitude denoted as h. Navigational system MSL altitude is h_{msl}, and sampled terrain elevation data is h_{dma}. The difference in these two values is the "predicted" AGL altitude ($h_{\mathrm{pred}} = h_{\mathrm{msl}} - h_{\mathrm{dma}}$), the method of determining height above ground in the baseline TF/TA guidance system. The accuracy of h_{pred} is determined by the accuracy of the navigation system and the terrain database. The radar altimeter measurement for AGL altitude is represented as h_{rad}. This measurement, along with the predicted measurement of AGL altitude, is to be blended to yield an improved estimate of h.

The accessed value for terrain elevation, h_{dma}, is an imperfect approximation of the terrain and is referenced using the imperfect latitude–longitude output from the navigation system. A level 1 Defense Mapping Agency (DMA) Digital Terrain Elevation Data (DTED) database consists of a uniform matrix of MSL terrain elevation values.[9] Unrecorded features and map horizontal shifts have been observed in flight tests.[3] Because the terrain elevation stored in the DMA database is accessed via the latitude–longitude value of the navigation system, horizontal positioning errors will reference offset terrain data. The sum of these h_{dma} errors, combined with those of the navigation system, can lead to large errors in the predicted absolute AGL altitude.

The radar altimeter is a direct measurement of the AGL altitude. Typical radar altimeters are limited in operational altitude and degrade in accuracy with altitude. Most are fan-type; i.e., a conical beam is transmitted, and height above ground or nearest obstacle is returned. The measurement is thus relatively insensitive to aircraft roll and pitch attitude and returns distance to the nearest terrain feature. The spreading of the radar beam "footprint" can yield radar altimeter returns registered from nearby higher terrain, rather than that directly below the aircraft. Flight over a dense forest may yield height above the treetops (canopy height), whereas flight over bare (winter) trees may give height above the ground.[10]

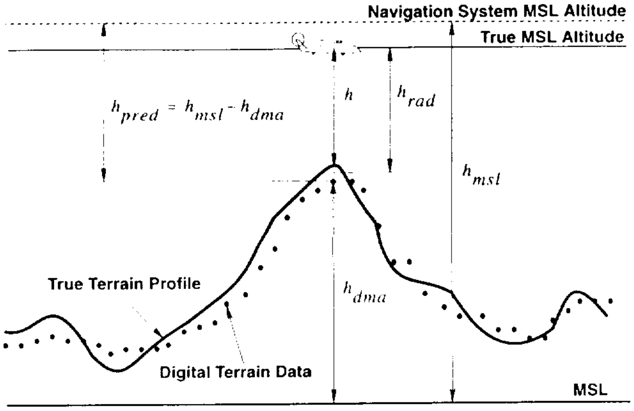

Fig. 1 Problem description.

Kalman Filter Implementation

A block diagram of the Kalman-filter-augmented terrain-referenced TF/TA guidance system is shown in Fig. 2. The dashed blocks describe the baseline terrain-referenced guidance system. The baseline system computes in real time a valley-seeking TF/TA trajectory based on a stored terrain elevation database, navigational aircraft state, and a nominal flight plan.[11] This trajectory is presented symbolically to the pilot on a helmet-mounted display (HMD).

A principal flight envelope constraint of any terrain database referenced guidance system derives from its ability to position the aircraft with respect to the terrain (Fig. 1). Such a limitation can be addressed by employing a terrain-referenced navigation system, which naturally connects the actual AGL altitude with that based on the terrain database. The baseline TF/TA guidance system studied here (Fig. 2), however, relies on airborne navigation only and had no ability to observe or reconcile such altitude differences. Combined vertical navigation and terrain database errors in the proposed flight test area established a minimum AGL altitude ceiling of 300 ft. Such flight altitudes greatly compromised the benefit and effectiveness of the TF/TA guidance system, particularly to the military helicopter community, where operations restricted to such midlevel altitudes would not justify its cost and complexity.

The solid blocks of Fig. 2 detail the extension to the baseline TF/TA system resulting from the Kalman filter augmentation. The predicted AGL altitude, calculated as the difference in the navigation system MSL altitude and the stored map terrain elevation, together with the radar altimeter measurement, are blended in a Kalman filter to yield an improved estimate of AGL altitude and an estimate for the difference error from the predicted AGL altitude. This difference error value, $\hat{h}_{\mathrm{err}}$, is then used to alter the terrain elevation database referenced guidance trajectory at the AGL-error blending block of Fig. 2. That is, the solely airborne navigation and stored terrain elevation database referenced trajectory of the baseline system ($[\rho_{\mathrm{traj}}]$) is modified with respect to the value of $\hat{h}_{\mathrm{err}}$ to produce $[\rho'_{\mathrm{traj}}]$.

The discrete-time Kalman filter is a recursive optimal control filter most appropriate for estimating a noisy signal given noisy measurements. The Kalman optimal criterion is the minimization of the mean-square error. The gains that satisfy this criterion are computed after each measurement sample. These gains take into account prior performance of measurements and states, in addition to a priori statistical knowledge of the random processes present. The Kalman filter recursive equations can be found in Brown.[12]

The author's earlier work detailed the design and non-real-time assessment of the Kalman filter formulations for the processing of the radar altimeter.[13] Only the recommended formulation will be described here.

The states are defined as

$$x_1 = h \tag{1}$$

$$x_2 = h_{\mathrm{err}} = h_{\mathrm{pred}} - h \tag{2}$$

The first state is the AGL altitude, and the second is the error between the first state and the predicted (navigation and terrain database)

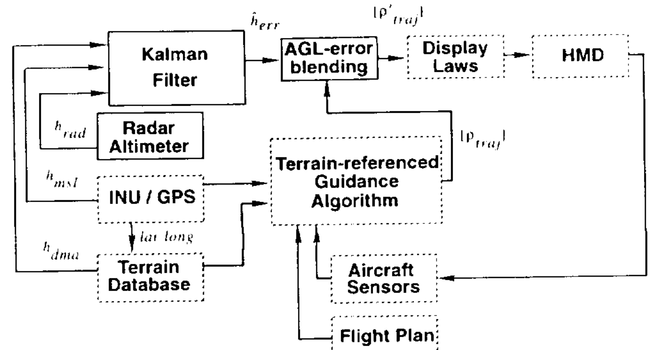

Fig. 2 Kalman-filter-augmented terrain-referenced guidance system. Baseline system components are shown as dashed.

AGL altitude. The explicit separation of the by-product state h_{err} in the state equations allowed for greater flexibility in flight test implementation of the filter.

The first state is modeled as a random walk:

$$\dot{x}_1 = w_1 \tag{3}$$

where w_1 is a Gaussian zero-mean white noise with variance σ_1^2 of $20^2 \mathrm{ft}^2/\mathrm{s}$. Physically, this describes a system driven by white noise, i.e., the random walk. The thought of using navigational vertical speed and DMA-based terrain slope in modeling this state is not reasonable in practice because of the great inaccuracy of calculated terrain slopes derived from so coarse a map in such (typically) rugged terrain. Potential benefit gained from such a model would not ensue is this application, and thus a random walk was employed.

The second state is modeled as a first-order Gauss–Markov process described by

$$\dot{x}_2 = -\beta x_2 + \sqrt{2\sigma_2^2 \beta}\, w_2 \tag{4}$$

where $1/\beta$ is the process time constant and w_2 is Gaussian zero-mean white noise with variance σ_2^2. A Gauss–Markov process is a stationary Gaussian process with an exponential autocorrelation of $E[x_2(t)x_2(t+\tau)] = \sigma_2^2 e^{-\beta|\tau|}$.

The measurement models are defined as

$$z_1 = h_{\mathrm{msl}} - h_{\mathrm{dma}} = x_1 + x_2 + v_1 \tag{5}$$

$$z_2 = h_{\mathrm{rad}} = x_1 + v_2 \tag{6}$$

where the measurement noises v_1 and v_2 are Gaussian zero-mean white-noise processes with variances 10^2 and 20^2 ft^2/s, respectively.

The first measurement, that of predicted AGL altitude, is modeled as the sum of a slowly varying bias (random walk) plus a first-order Markov process. This measurement is expected to be quite smooth and reliable, although it will carry a bias due to both the navigation vertical position solution and the stored terrain database (DMA map). Some degree of correlation between measurements, however, is addressed with the Markov process. The radar altimeter complements the navigation/terrain database measurement in registering higher frequency absolute height-above-ground movements. The bias of the radar altimeter measurement is reflected in the random-walk model. Similar models for terrain-referenced altitude errors have been employed in the literature.[14] Many models establish a priori statistical values (e.g., variances) of some states or measurements based on statistics of the stored terrain elevation map involved.[15] This is done principally to enhance performance/optimality of the Kalman filter and to increase robustness in the event of abrupt bias changes at DMA map boundaries.

In this work, spectral analysis of flight and map data in the proposed flight test areas established $1/\beta$ at 10 s and σ_2^2 at $45^2 \mathrm{ft}^2$. Note that a $1/\beta$ of 10 s corresponds to an along-track distance of $\sim\frac{1}{4}$ mile for an aircraft flying at 90 knots. Such values were found appropriate for the mild to moderately rugged flight test areas and speeds (80–110 knots) encountered and expected during TF/TA guidance system operation.

In discrete-time, state-space form, the linear state models are

$$x_{k+1} = \Phi_k x_k + \omega_k \tag{7}$$

where

$$\Phi_k = \begin{bmatrix} 1 & 0 \\ 0 & e^{-\beta\Delta t} \end{bmatrix}$$

and the measurements

$$z_k = H_k x_k + v_k \tag{8}$$

where

$$H_k = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$$

The Kalman filter is implemented to process the measurements sequentially, an established procedure[12,16] that allows a measurement rejection test to be applied. The structure of the filter matrix equations remains unchanged, but the measurement matrix H_k becomes a row vector and the measurement covariance matrix R_k becomes a scalar corresponding to the scalar measurement z_k being processed.

The rejection test compares each measurement with that predicted from the measurement model

$$\hat{z}_k = h_k \hat{x}_{\bar{k}} \tag{9}$$

whereby a measurement deemed statistically unreasonable is thrown out and not used to update the state and error covariance matrices. The measurement residual

$$\rho_k = z_k - \hat{z}_k \tag{10}$$

is compared with the expected standard deviation of that measurement,

$$\alpha_k = \sqrt{h_k P_{\bar{k}} h_k^T + r_k} \tag{11}$$

in determining acceptance of a measurement. Note that $P_k = E[(x_k - \hat{x}_{\bar{k}})(x_k - \hat{x}_{\bar{k}})^T]$ is the error covariance matrix.

In this work, a two-standard-deviation ($2\alpha_1$) criterion was established for ρ_1 (residual from navigation/terrain database predicted AGL altitude measurement) and a $4\alpha_2$ criterion for ρ_2 (radar altimeter measurement residual). Thus, if ρ_1 exceeded $2\alpha_1$, or if ρ_2 was greater than $4\alpha_2$, that measurement was discarded. These thresholds were set based on the behavior of the instruments used in acquiring the flight test data considered in this report. Such rejection limits would have to be adjusted for different measurement sources than those considered here and possibly for flight conditions (e.g., poor GPS satellite navigation data due to satellite geometry or intermittent reception). For numerical stability, the symmetric error covariance matrix P_k was forced to remain symmetric after every measurement update by averaging the off-diagonal elements. Divergence of a Kalman filter without such a constraint is well documented.[12,16]

The reader may ponder the logic behind the two-state Kalman formulation presented versus that of a more traditional complementary filter using the radar altimeter measurement alone. The Kalman structure used adds a necessary degree of redundancy in using both AGL measurements, i.e., the radar altimeter direct measurement and that found by subtracting the DMA map terrain elevation from the navigational MSL. This allows updating of the state variable of prime interest, AGL altitude error, during occasional dropouts of the radar altimeter. Such dropouts are not unusual and would otherwise result in a filter "dead-reckoning" for AGL and thus AGL error. Also, the use of the two-state Kalman filter, as implemented to allow sequential processing of its asynchronous measurements, allows the statistically based rejection tests described to be applied to each of these measurements. Such measurement checks were quite useful in addressing errant radar altimeter "spikes" and occasional navigation irregularities during satellite dropouts.

A more detailed understanding of the presentation of the guidance trajectory to the pilot is necessary in order to complete the description of the Kalman filter implementation. A simplified pictorial of the pilot presentation symbology on the head-tracked helmet-mounted display is shown as Fig. 3. The pathway troughs and phantom aircraft are drawn in inertial space along the desired trajectory. The troughs are 100 ft wide at the base, 50 ft tall, and 200 ft wide at top and are drawn in 1-s increments of the trajectory

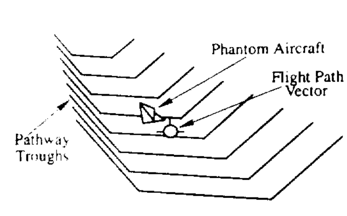

Fig. 3 Pilot display.

out to 8 s, based on the aircraft's airspeed. The top center of each pathway is the desired, computed trajectory. The phantom aircraft dutifully flies at the top center of the forth trough (the desired trajectory 4 s in the future). The aircraft's flight-path vector is also drawn on the helmet-mounted display, as predicted 4 s ahead. Hence, by tracking the phantom aircraft with the flight-path vector, the pilot is able to fly the desired TF/TA guidance trajectory. Additional aircraft status information is also displayed but not shown here, e.g., airspeed and heading. This symbology set was developed over several piloted, motion-based simulations with a diverse group of pilots and gives good trajectory tracking performance with low pilot workload.[8]

The inertial symbology of Fig. 3 is drawn based entirely on the aircraft's airborne navigation and its stored terrain elevation database and is the crux of the terrain referencing problem. The Kalman filter's estimate of $\hat{h}_{err}$ is used to correct for navigation and terrain database error by repositioning this trajectory. In order to ensure a smooth symbology presentation of the guidance trajectory to the pilot, the change in the value of $\hat{h}_{err}$ is ramped in linearly over the eight troughs presented. That is (after initialization) the eighth trough is altered in the vertical position by the full change in $\hat{h}_{err}$, but the first trough is only moved by one-eighth, of this $\Delta\hat{h}_{err}$. Such "ramping" does introduce a lag in the trajectory symbology, although the scheme is bounded at the eighth trough by the current value of $\hat{h}_{err}$. This method of modifying the trajectory AGL placement was verified in a piloted, motion-based simulation and retains the mature symbology set of the baseline TF/TA guidance system.

Aircraft Integration

The Kalman-filter-augmented terrain-referenced guidance system was implemented and flight tested aboard a modified Sikorsky NUH-60A Blackhawk helicopter. The Systems Testbed for Avionics Research (STAR) aircraft is operated by the U.S. Army, Fort Monmouth, New Jersey (Fig. 4). The components of the NUH-60A STAR are cataloged in Table 1. The NUH-60A STAR hosts the Army Digital Avionics System (ADAS). This system allows fully integrated control and display capabilities for the pilot and copilot through two identical pairs of multifunction displays. These displays provide digital monitoring of aircraft state and instrumentation and associated control. A flight engineer station at the rear of the aircraft includes an additional ADAS display for flight test direction and control. All components of this network are connected through a 1553B interface.

The principal flight computer for the guidance system is a Motorola 68030 and 68020 multiprocessor VME computer. The VME computer acts as the central processor for the research work conducted on the aircraft and is interfaced to several other computers and devices. A 1553B interface connects the VME to the INU (32 Hz), GPS (1 Hz), IHADSS (32 Hz), radar altimeter (8 Hz), and IBM PS/2 (8 Hz), the latter used as a route planner. The fiber-optic Scramnet network is used to connect the VME with the Silicon Graphics computer (20 Hz), which generates the display symbology. The Kalman filter resides on the VME computer, with each of its distinct measurement processing loops triggered by the incoming measurements.

Navigation is provided by an integrated two-channel precision-code GPS receiver and platform-stabilized INU. GPS accuracy, as displayed by the GPS receiver, is typically 33 ft (10 m) circular error probable (CEP) horizontal and 53 ft (16 m) vertical. The fan-type 4.3-GHz radar altimeter returned height above ground or closest terrain obstacle to altitudes of 1500 ft and through pitch and roll angles of 45 deg. Radar altimeter accuracy is specified to be 3 ft ±3% of actual altitude.[10]

The terrain elevation database was level 1 DMA DTED in the 1 deg × 1 deg cells from 77 deg to 78 deg W longitude and from 39 deg to 41 deg N latitude. Database prediction of terrain elevation is found by forming a triangular plane of the nearest three "posts" of DMA data. The interpolated value of this plane below the aircraft is taken as the database elevation prediction.

Flight data were recorded at 5 Hz and included the Kalman filter output of $\hat{h}_{err}$ and sampled values of radar altimeter and navigational state information. Infrared video was also recorded.

Table 1 Test aircraft components

Component	Manufacturer/model
Aircraft	U.S. Army Sikorsky NUH-60A Blackhawk helicopter
Flight computers	Motorola 68030, 68020 VME Silicon graphics 4D/120 IBM PS/2
Pilot display	Honeywell IHADSS
Navigation	Litton LN-39 INU, Rockwell-Collins RCVR-OH GPS receiver
Radar altimeter	Honeywell APN-209
Terrain database	DMA level I digital terrain elevation data (DTED)
Other	FLIR Systems 2000 infrared camera

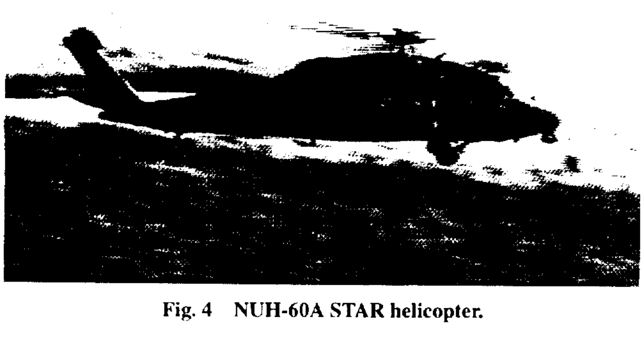

Fig. 4 NUH-60A STAR helicopter.

Flight Test Results

The flight test evaluation of the Kalman-filter-augmented system and the baseline system was conducted in moderately rough terrain just south of Harrisburg, PA. The area includes diverse features, such as flat plain sections and South Mountain, running diagonally northeast–southwest through the test area. The more rugged sections of the region contain rather densely populated deciduous trees. Areas of strip mining and clear cutting were also present. Flight data discussed and presented in this report were collected during winter of 1992/1993 and spring 1993.

The evaluation of the terrain-referenced guidance system included assorted combinations of speed, set clearance altitude, trajectory algorithm TF vs TA weighting, and pilot display options over a test course of several waypoints. A partial flight test ground track is shown in Fig. 5. The reference origin of the test area corresponds to 40 deg 03′45″ N latitude, 77 deg 18′45″ W longitude. The TF/TA guidance algorithm, which is not required to pass directly over any given waypoint, is computing a valley-seeking low-altitude path in

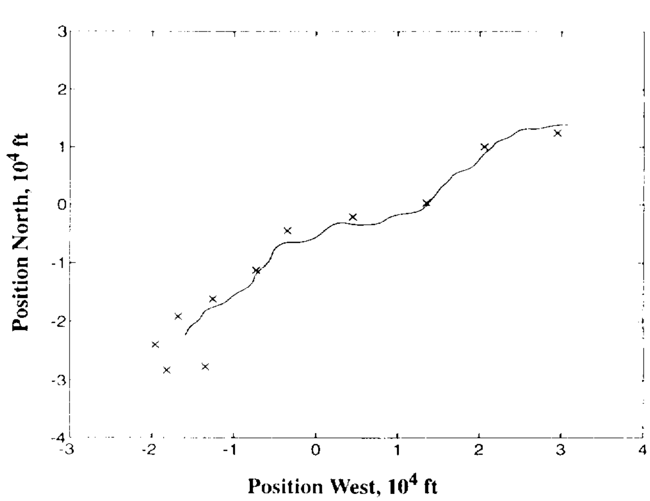

Fig. 5 Flight test course. A typical TF/TA mission is shown from waypoint 2 through 9.

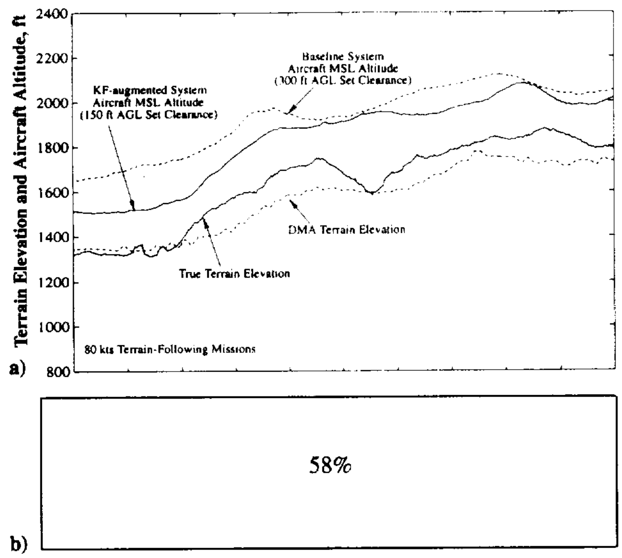

Fig. 6 Baseline and Kalman-filter- (KF-) augmented terrain-referenced guidance system during TF mission. Kalman-filter-augmented system allows for lower and more accurate flight above terrain than baseline system.

the test region. A flight test mission for a particular flight mission configuration begins at waypoint 2 in the northeast, follows a meandering trajectory to the southwest, loops around waypoints 9–12, and then retraces the course from 8 to 2. A typical 80-knot flight covers the 20-nautical-mile course in about 20 min. Note that because the guidance algorithm computes a trajectory solution in real time based on the aircraft state, stored terrain data, mission flight plan, and aircraft state history (Fig. 2), no two test missions will be identical.

The vertical flight profiles of a representative portion of two separate 80-knot TF missions are presented as Fig. 6a. Terrain-following flight, or contour flight, is flown at constant heading between waypoints with only vertical maneuvering. The ground track of such flight results in straight lines between waypoints. These two flights, flown between waypoints 8 and 10, produced nearly identical ground tracks and hence were over the same terrain. The dashed upper line traces the aircraft MSL altitude while configured with the baseline terrain-referenced guidance system at 300 ft set clearance altitude. (Set clearance altitude is that AGL altitude selected by the pilot to which the guidance algorithm will nominally produce.) The solid line near it tracks the aircraft MSL altitude during another flight with the Kalman filter radar altimeter-enhanced system at 150 ft set clearance. The stored DMA digital map prediction of terrain elevation is shown as the lower dashed line of Fig. 6a, and the aircraft's MSL altitude minus radar altimeter measurement (during the 150-ft AGL flight) is given as a "truth" measurement of the terrain elevation. In this region, vertical navigation error and horizontal navigation error (as given by the GPS) were both 30 ft. Combined vertical navigation error and radar altimeter error sets this truth estimate of the terrain elevation to within 40 ft. During the baseline system flight, vertical navigation error was 43 ft and horizontal navigation error was 23 ft.

The vertical accuracy limitation of the digitized terrain elevation data is markedly apparent from Fig. 6a. During the first 20 s of the flight, the DMA prediction is nearly identical to that of the truth terrain. The following hills, however, from 20 to 55 s, and then from 55 to 100 s, are drastically underestimated and smoothed by over 150 ft in sections. Other flight test missions and regions revealed DMA underestimation of terrain by as much as 300 ft. Note that overestimation of the actual terrain in the stored terrain elevation database would result in a baseline terrain-referenced trajectory higher than desired in actual AGL altitude. In the military application higher altitudes translate to greater exposure and risk to ground-based threats. An underestimation of terrain elevation by the database would translate to lower than desired trajectories above the terrain. This could lead to a ground collision.

In the first 20 s of flight, the DMA accurately places the terrain at about 1350 ft MSL. The baseline guidance system results in an aircraft altitude of 1650–1700 ft, or 300–350 ft above the terrain, in general agreement with the 300 ft set clearance selected. Similarly, the Kalman-filter-augmented system results in a flight path around 1500 ft MSL, approximately 150 ft above the terrain and approximately the set clearance altitude selected for that flight. The benefit of the Kalman filter integration of the radar altimeter is first realized when the hill from 20 to 55 s is traversed. As the terrain rises to a peak of 1750 ft, the Kalman-filter-augmented system maintains an AGL clearance between 140 and 230 ft, whereas the baseline system, triggering solely on the DMA predicted terrain, brings the aircraft from 170 to 360 ft above the ground. The closest separation to the ground (170 ft) occurs at the hilltop of 45 s. Similar terrain tracking differences are evident in the second hill from 60 to 100 s, where the DMA representation of the terrain is again too low. The KF improved system generally maintains a separation above the ground of 140–220 ft, very near the 150-ft AGL altitude desired. The radar altimeter enhancement provided by the Kalman filter is allowing the aircraft to fly a trajectory more reflective of the true topography at a lower AGL set clearance altitude than that provided by the baseline system.

The aircraft trajectories flown differ slightly from those computed and presented to the pilot for tracking on the helmet-mounted display. Pilot tracking inconsistencies are apparent during the Kalman-filter-augmented system flight of Fig. 6a when the system appears not to react to the valley at 55 s and to balloon over the terrain from 80 to 90 s. In fact, the system did react to this valley, as evident from the Kalman filter estimate $\hat{h}_{err}$ of AGL altitude error during this period (Fig. 6b). Although the Kalman filter estimator did provide a correction that brought the trajectory into the valley and without the hill overshoot, this trajectory was not followed very rigorously during these two periods. Although the trajectory commanded is constrained to be within the aircraft's performance capabilities, the pilot can never track the symbology perfectly and at times will override the recommended pathway. Circumvention of the commanded trajectory occurs most often when an obstacle, such as a tree or wire, is encountered. Such obstacle avoidance is the pilot's responsibility and is a fundamental limitation of both the baseline terrain-referenced guidance system and the Kalman-filter-augmented system. The Kalman filter enhancement, although able to substantially improve AGL positioning of the aircraft and hence reduce the minimum operational altitudes of the system, has no look-ahead capability for obstacles and limited predictive abilities of the terrain (ground) itself.

Figure 7a traces a 5-minute section of a TF/TA flight with the Kalman filter's processing of the radar altimeter at 100 knots and 150 ft set clearance altitude. The region described is between waypoints 2 and 8 (Fig. 5). The lower dashed line tracks the DMA prediction of terrain elevation, whereas the lower solid line describes the "true" elevation, as calculated by subtracting the aircraft's radar altimeter return from its navigational MSL altitude. During this flight, vertical navigation error was 41 ft and horizontal error 28 ft (from a GPS receiver). This places the calculated truth terrain elevation to within 50 ft.

The upper dashed and solid lines of Fig. 7a are the desired (or "commanded") trajectory MSL altitude and the actual aircraft MSL altitude, respectively. The commanded trajectory is that computed by the trajectory algorithm (and subsequently modified in altitude using the Kalman filter output) and presented to the pilot using the display symbology. As mentioned, due to the human (pilot) element, however, this commanded trajectory altitude is never exactly followed. During the majority of the flight, the commanded and actual MSL altitude of the aircraft are in general agreement. The several unmodeled hills are recognized by the Kalman-filter-augmented system and flight at approximately 150 ft AGL is maintained. There are periods where the pilot had difficulty tracking the symbology, at times overcontrolling and then having to "catch" the trajectory. During the flight documented in Fig. 7a, pilot tracking of the desired commanded trajectory was of 2.5 ft mean error laterally, $\sigma = 17.8$ ft, and 0.7 ft mean error vertically, $\sigma = 18.9$ ft. Such pilot tracking performance was typical throughput the flight evaluation.

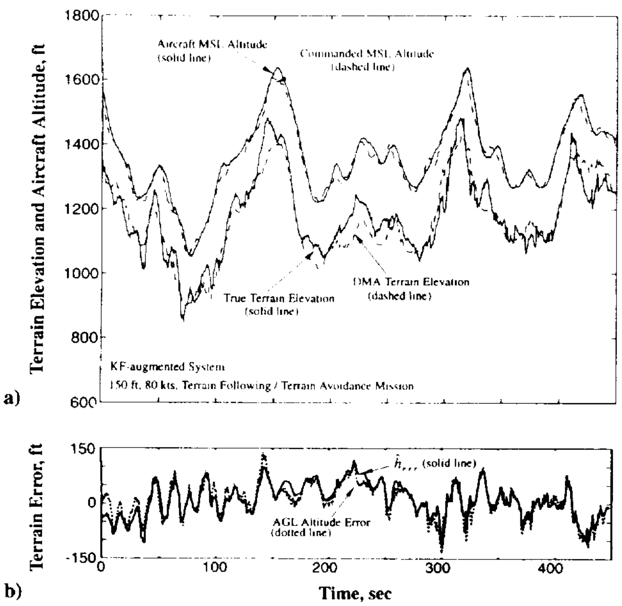

Fig. 7 **Kalman-filter- (KF-) augmented terrain-referenced guidance system during a TF/TA mission. Kalman-filter-augmented commanded trajectory accurately follows true topography, although pilot does not follow this trajectory exactly.**

The general relationship between the aircraft's actual vertical flight path and that commanded by the radar altimeter-enhanced system is that of a slight lag and slightly higher and smoother flight paths.

The several unmodeled hills (e.g., those centered at 140, 230, and 320 s), at times over 140 ft higher than that predicted by the stored DMA database of terrain elevations, are clearly recognized by the radar altimeter and processed by the Kalman filter. Flight over these regions is maintained nominally at 150 ft, the desired set clearance altitude. Figure 7b traces the Kalman filter estimate of $\hat{h}_{err}$ during the 150 ft Kalman-filter-augmented system flight. It must be emphasized that flight at this set clearance without the Kalman filter, i.e., by the baseline, solely DMA dependent system, could not have been attempted, as the terrain database errors surely would have resulted in a ground collision.

Histograms of AGL altitude of representative TF and TF/TA flights with and without the Kalman filter enhancement are given as Fig. 8. The Kalman filter processing of the radar altimeter clearly tightens up the spread of the aircraft clearance above the terrain while reducing the number of incursions greater than 50 ft below the desired set clearance altitude. The 50-ft threshold corresponds with the bottom of the guidance trajectory trough symbology and is a natural boundary value to consider. For the TF flights, time at or below 50 ft of set clearance (i.e., ≤ 250 ft) for the baseline system was 28.7%, while that for the Kalman-filter-augmented system (i.e., ≤ 100 ft) was 2.9%. For the TF/TA mission, flight below this 50 ft threshold was 10.2% for the baseline system and 4.9% for the Kalman-filter-augmented system.

The mean values and standard deviations of the four flight scenarios of Fig. 8 allow the calculation of the probability of 0 ft AGL clearance occurring, i.e., the "probability of clobber." For the TF missions, $P(h_{agl} \leq 0)$ is 3×10^{-5} for the baseline system at 300 ft set clearance altitude and 4×10^{-4} for the Kalman-filter-augmented system at 150 ft set clearance. For the TF/TA mission, $P(h_{agl} \leq 0)$ is 2×10^{-5} for the 300-ft clearance altitude baseline system and 2×10^{-4} for the 150-ft clearance-enhanced system. Such values compare with the maximum failure rate for flight control systems of 1×10^{-5} in MIL-F-9490D.[1]

The Kalman filter radar altimeter enhancement to the terrain-referenced guidance system was flown and assessed over the entire flight test envelope of the baseline system. Test variations for the Kalman-filter-enhanced system included aircraft performance (speeds of 80 and 110 knots), maximum bank angle (20 deg and 30 deg), trajectory algorithm settings (TF, TF/TA flight), and assorted display symbology options. Flights in the greater Stratford, Connecticut, area and in the extremely flat terrain around Lakehurst NAS, New Jersey, were also made, in addition to flights across DMA terrain map boundaries in the Pennsylvania test area. Reduced AGL clearance performance or irregular behavior of the Kalman filter enhancement described was not observed in these conditions.

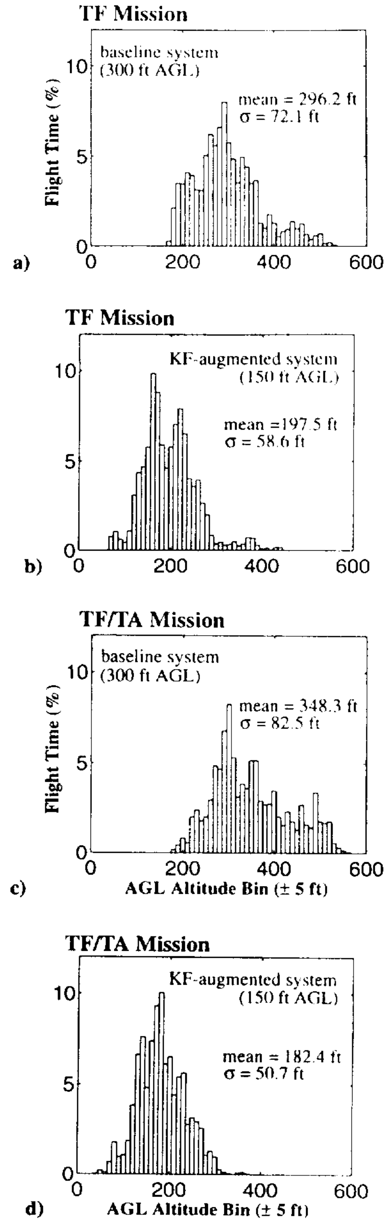

Fig. 8 Histograms of guidance system AGL altitude.

Throughout the extensive array of flight conditions evaluated, the test pilots felt that the enhanced Kalman filter system created a reliable and more accurate low-altitude guidance trajectory than the baseline system and trajectories deemed more representative of the contours and topography of the region. The enhanced system allowed for lower flight altitudes and closer adherence (shown by the tighter AGL altitude histograms) to the desired clearance altitude above the terrain. The "ramping" in of the Kalman filter estimate of the AGL referencing error of the baseline system into the trajectory symbology presentation was found to be very smooth and satisfying to the pilots.

Concluding Remarks

1) A Kalman filter state estimator was developed to improve the AGL positioning of a terrain-referenced guidance system, as warranted by vertical navigation error and stored terrain database

error. The filter incorporates a radar altimeter measurement of height above ground to estimate the error present in the vertical positioning of trajectories generated by a baseline terrain-referenced guidance system. The Kalman filter modified trajectory is presented to the pilot on a helmet-mounted display.

2) The filter was implemented for real-time operation aboard a U.S. Army Blackhawk helicopter. The resulting augmented system was flight tested in moderately rugged terrain under a wide range of test conditions.

3) The Kalman filter processing of the radar altimeter measurement was found robust and accurate in modifying the vertical position of the baseline terrain-referenced guidance system trajectories. The enhancement produced trajectories more reflective of the topography and allowed for lower altitude operation than that of the baseline guidance system. The minimum flight altitude was reduced from 300 ft AGL altitude to 150 ft at operational speeds from 80 to 110 knots.

Flight restrictions for the terrain-referenced guidance system are now governed by pilot obstacle detection and avoidance, which could be assisted by a forward-looking sensor. Work involving a laser radar sensor in this role is being conducted.[17]

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